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11

REVIEW OF THE EFFECT OF DISTRIBUTED SURFACE ROUGHNESS ON BOUNDARY-LAYER TRANSITION

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SUMMARY

Presented in this paper is a discussion of the transition phenomena associated with distributed roughness, a correlation of three-dimensional roughness effects at both subsonic and supersonic speeds, and the effect of laminar boundary-layer stability as influenced by heat transfer, pressure gradients, and boundary-layer control on the sensitivity of laminar flow to distributed roughness. The results presented indicate that the transition-triggering mechanism of three-dimensional-type surface roughness appears to be the same at supersonic and subsonic speeds. In either case, a Reynolds number based on the height of the roughness and the local flow conditions at the top of the roughness can be used to predict with reasonable accuracy the height of three-dimensional roughness required to cause premature transition. Neither the three-dimensional roughness Reynolds number nor the lateral spread of turbulence behind the roughness is changed to any important extent by increasing the laminar boundary-layer stability to theoretically small disturbances. Therefore, for a given stream Mach number and Reynolds number, surface cooling, boundary-layer suction, or a favorable pressure gradient will, in the presence of three-dimensional roughness, promote rather than delay transition.

INTRODUCTION

Sufficient experimental information has been accumulated to indicate that boundary-layer turbulence always starts from point-like turbulent spots which grow in size with downstream movement and finally merge to form a continuously turbulent region. Although this appears to be so regardless of the type of initial disturbance present, the most upstream location of the continuously turbulent flow depends upon the type and magnitude of the initial disturbance such as stream turbulence level or surface protuberances. This paper will deal with the effects on boundary-layer transition of discrete particles of roughness, that is, particles of a three-dimensional nature such as sand grains or rivets or spattered bugs. Two-dimensional roughness such as spanwise ridges will be discussed only to compare the transition phenomena with the three-dimensional roughness case.

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SYMBOLS

d	width or diameter of roughness particle
k	height of roughness particle
M	Mach number
R	Reynolds number based on free-stream conditions
R_k	Reynolds number based on roughness height and local flow conditions at top of roughness, $\frac{u_k k}{\nu_k}$
u	local streamwise component of velocity in boundary layer
ν	coefficient of kinematic viscosity

Subscripts:

k	conditions at top of roughness particle
o	local conditions outside boundary layer
t	conditions at which turbulent spots appear
w	conditions at wall
∞	conditions in undisturbed free stream

DISCUSSION

It has been found that, for discrete particles of roughness, a critical size exists below which the roughness has no influence on the natural transition and above which the roughness causes premature transition. This is shown in the first figure by means of several observations of the variation of the streamwise boundary-layer velocity fluctuations with time. These measurements were made with the use of a hot-wire anemometer on a 10° included angle cone at a Mach number of 2.01. The vertical location of a trace indicates the corresponding Reynolds number per foot of the stream. The left group of traces was obtained through a Reynolds number range for a smooth cone. The bottom trace indicates completely laminar flow. The next higher indicates occasional bursts of turbulent flow. The next higher indicates laminar flow a small part of the time, and the top one, fully turbulent flow. All traces were made with the hot wire at the same location. This change in the character of the boundary layer with changes in Reynolds number is consistent with the Schubauer-Klebanoff description of the origin of turbulence at subsonic speeds (ref. 1), that is, it is consistent with the concept of transition beginning as turbulent spots that start in the vicinity of the roughness and grow as they move downstream. Shadowgraphs taken at the Ames Research Center of NASA (ref. 2) verify the existence of turbulent spots at supersonic speeds.

On the upper right part of the figure are shown hot-wire traces taken behind some granular roughness on the cone. This roughness was 0.003 inch high but had no effect on the natural transition as seen by the fact that the turbulence was initiated at the same value of stream unit Reynolds number. In contrast, the traces on the lower right part of the figure, taken behind a larger size roughness, show a large reduction in stream unit Reynolds number for the initiation of turbulence. This comparison clearly indicates that a critical size of this three-dimensional roughness does exist. Other hot-wire measurements have also shown that for three-dimensional roughness only slightly smaller than the critical size, the level of the velocity fluctuations in the laminar layer at appreciable distances downstream of the roughness was as low as that measured with a smooth surface (ref. 3). It appears then that no upstream movement of the transition region occurs at speeds below the critical speed of the roughness.

From measurements of the type shown in figure 1, it seems likely that for three-dimensional roughness, transition results from formation of discrete eddies or disturbances originating at the roughness particles. We should then be able to relate the occurrence of these disturbances to the local flow conditions at the roughness. This has been done at subsonic speeds on the basis of a critical roughness Reynolds number formed with the height of the roughness and the local flow conditions at the top of the particle when the particle began to introduce turbulent spots into the boundary layer. The square root of this critical roughness Reynolds number is equal to a correlation Reynolds number originally proposed by Schiller on the basis of the roughness height and the friction velocity.

Numerous data points from several low-speed investigations of three-dimensional roughness particles are presented in figure 2 in the form of the square root of the roughness Reynolds number for transition plotted against the ratio of the particle width or diameter to the particle height. These data cover a wide range of particle shape, distribution, number, height, distance from model leading edge, and degree of boundary-layer stability as affected by pressure gradient and boundary-layer control. Included are cylindrical roughness particles in a small favorable pressure gradient, cylindrical particles with the boundary layer stabilized by area suction, cylinders in a zero pressure gradient, conical particles in a small favorable pressure gradient, spheres in a zero pressure gradient, and angular particles, spherical particles, and surface craters with raised edges around the rim, all in a strong favorable pressure gradient. Because of the considerable overlapping of the large number of points available, many of them have not been plotted but are listed in the table at the top of the figure. The range of values of $\sqrt{R_{k,t}}$ covered by each group of additional points is shown and the arrowheads indicate the corresponding values of d/k. Some of the scatter in the measured values of the critical roughness Reynolds number parameter is due to differences in experimental methods of obtaining the indications of the initiation of turbulence. Nevertheless, in spite of the large differences in roughness configuration and experimental technique, the values of $\sqrt{R_{k,t}}$ for a given value of d/k are seen to vary only within a factor of about 2. For roughness within the linear portion of the boundary-layer velocity distribution, $\sqrt{R_{k,t}}$ is proportional to the critical projection height. This correlation, therefore, can be used to indicate within the same accuracy the magnitude of a submerged three-dimensional type of roughness necessary to cause premature transition. For roughness heights equal to or greater than the total boundary-layer thickness, there are some data that indicate somewhat larger values of the critical roughness Reynolds number (refs. 3 and 4). It should be noted, however, that for these heights, the condition of flow similarity about the particles, upon which the concept of a critical roughness Reynolds number is based, is not satisfied.

The variety of shapes presented in figure 2 is seen to form some systematic variation of $\sqrt{R_{k,t}}$ with d/k, a decreasing value of the roughness parameter with increasing d/k. This is reasonable inasmuch as projections with large values of d/k are approaching protuberances of a two-dimensional nature, and the laminar boundary layer has been found to be more sensitive to two-dimensional than to three-dimensional disturbances.

If a greater degree of accuracy is desired for particular applications than that provided by the order of magnitude correlation of figure 2, more information is required on the secondary effects of such factors as particle shape and distribution. Some indication of the effect of distribution of cylindrical particles has been obtained by Cowled (ref. 11) and Carmichael (ref. 12). The effect of spanwise spacing is shown in figure 3 in the form of the ratio of critical roughness Reynolds number for a pair of projections to the critical roughness Reynolds number for a single projection plotted against the ratio of spanwise projection spacing to the cylinder diameter. Cowled had shown that a spanwise spacing of projections equal to 3 times the projection diameter had no effect on the critical roughness height as compared with a single projection. Carmichael's results presented here also show no effect at the large spacing. These data, however, show that for a closer spanwise spacing, the height of the critical roughness decreases. Such a result would be expected because the closer spacing corresponds to more of a two-dimensional-type obstacle to the flow and, as was shown in the previous figure, the critical roughness Reynolds number is lower for two-dimensional than for three-dimensional roughness. Figure 4, which presents the effect of streamwise spacing as obtained by Carmichael (ref. 12), indicates that for close streamwise spacing, the critical roughness height increases somewhat. This probably results from a tendency of the rearward particle to delay the formation of eddies around the first particle.

Now let us consider the problem of the correlation of transition induced by three-dimensional roughness at supersonic speeds. At supersonic speeds, we not only have a variation of velocity through the boundary layer but also a variation of kinematic viscosity due to the temperature distribution. For this condition, several methods for correlating the roughness-induced transition have been suggested but we have elected to try a roughness Reynolds number similar to the one used at subsonic speeds. In order to reduce the effect of Mach number on the roughness Reynolds number, local values of density and viscosity at the top of the particle were used as well as the velocity at the particle height. I should mention that these values are for the conditions in the boundary layer without the particle present. Results obtained at the Langley Research Center (ref. 13) and by Dr. van Driest at the Jet Propulsion Laboratory (ref. 14) are presented in figure 5 in the form of the $\sqrt{R_{k,t}}$ plotted against surface Mach number. The square root of the critical roughness Reynolds number was again chosen because it is more nearly proportional to the critical projection height than is $R_{k,t}$, although at supersonic speeds, the exponent of $R_{k,t}$ for linearity with k is even smaller than 1/2. The spread in critical roughness height, then, would be less than indicated in this figure. The circle symbols are for spherical roughness particles on a flat plate, the squares for granular particles on a cone, and the diamonds for spherical particles on a cone. Comparison of these results with the low-speed data of figure 2 indicates that about the same value of critical roughness Reynolds number can be used, for practical purposes, to predict the initiation of turbulence at least up to a Mach number of about 4. This result is particularly significant inasmuch as it indicates that for surface temperatures near adiabatic-wall values, the roughness height required to cause transition is greater at supersonic than at subsonic speeds because of the boundary-layer thickening effect of Mach number in supersonic flow. Additional experimental information on the critical roughness Reynolds number at higher supersonic and hypersonic speeds is required.

The possible effects of laminar boundary-layer stability on the critical roughness size are next considered. We know that boundary-layer cooling, boundary-layer suction, and favorable pressure gradients have a stabilizing effect on the laminar layer for small disturbances. In a stable laminar layer, these small disturbances damp out as they move downstream and the extent of laminar flow over a smooth surface can be greater than for the unstable case. (The effectiveness of cooling and of continuous suction is shown in references 15 to 18, and 19, respectively.) In figure 6 are presented additional hot-wire traces behind three-dimensional roughness elements of finite size. The measurements were made on a 10° cone for a Mach number of 2.01 and are representative of similar measurements made at a Mach number of 4.21. The left group of traces was made with the model surface at equilibrium temperature and the right group for the same surface roughness but with the model cooled. The wall-temperature distribution for the cooled model is shown in the upper right-hand corner. The wall temperature varied from almost stagnation near the cone apex to about -50° F ahead of the roughness.

It is clearly demonstrated that for the stream unit Reynolds number at which the roughness was just critical, that is, when turbulent spots began to appear with the surface at equilibrium temperature, cooling the cone surface resulted in a completely turbulent boundary layer. In fact, for the cooled condition, it was necessary to decrease appreciably the stream unit Reynolds number in order to return the boundary layer to the laminar condition. Associated with the surface cooling for given values of roughness size and location and stream Reynolds number and Mach number is an increase in the actual roughness Reynolds number R_k. This increase is caused by, first, an increase in velocity at the top of the particle due to a thinning of the boundary layer and due to an increase in convexity of the velocity profile and, second, an increase in local density and a decrease in local viscosity due to the lowered boundary-layer temperature. The fact that transition resulted from this increase in roughness Reynolds number indicates that the critical value of roughness Reynolds number was not increased to any important extent by the theoretical increase in laminar boundary-layer stability resulting from the surface cooling. This conclusion is verified by referring to figure 5. Close agreement is seen between the filled-in square symbols, which represent values of the roughness parameter $\sqrt{R_{k,t}}$ for the cooled cone, and the open square symbols, which represent values for the cone at recovery temperature. These values are also in close agreement with the low-speed data of figure 2 where increased laminar stability was obtained either by continuous suction or by a highly favorable pressure gradient. For this large variety of conditions, an increase in laminar boundary-layer stability had very little effect on the roughness Reynolds number parameter for transition.

It should be noted, however, that for two-dimensional roughness such as spanwise ridges or grooves, laminar stability can have a beneficial effect on the allowable roughness. Recent evidence of this can be found in an I.A.S. paper by van Driest and Boison (ref. 18) for the laminar layer made stable by means of surface cooling and, secondly, from some tests of spanwise wires on a large sphere where an increase in stability resulted from the favorable pressure gradient (ref. 10). The difference in the effect of laminar boundary-layer stability on the initiation of turbulence caused by two- or three-dimensional-type roughness is associated with a basic difference in the triggering mechanism of turbulence for the two types of roughness. Hot-wire measurements have shown that, for the three-dimensional roughness, the turbulent spots are initiated at the roughness when the local Reynolds number becomes critical. For two-dimensional roughness, turbulent spots are first noted at a rearward position with no turbulence forward and a further increase in Reynolds number is required to move the transition gradually forward (e.g., ref. 20). The disturbances produced by the two-dimensional roughness, therefore, appear to be of the Tollmein-Schlichting type and are subject to amplification theories during their movement downstream. For the three-dimensional roughness, however, the turbulent spots appear to be initiated directly at the roughness and there is no room for the stability arguments to apply.

It should be worthwhile at this point to focus attention on the interval in roughness Reynolds number between the value at which turbulent bursts are first initiated in the boundary layer and that at which a fully developed turbulent boundary layer exists in the immediate vicinity of the three-dimensional roughness. The latter case, of course, is important in determination of the condition for which turbulent heat-transfer and skin-friction characteristics are obtained. At subsonic speeds, this interval in Reynolds number was found to be very small; however, at supersonic speeds some information has been obtained indicating a larger interval in Reynolds number. In a paper by van Driest and McCauley (ref. 14) are presented measurements of the position of fully developed turbulent flow behind a spherical roughness particle as a function of stream unit Reynolds number. These data have been converted in figure 7 to plots of $\sqrt{R_k}$ for various distances of the fully developed turbulent flow behind the roughness. The roughness was located 5 inches from the leading edge of a 10° included angle cone. At a surface Mach number of 1.90, three roughness heights were investigated. For each roughness height, the most downstream point indicates the minimum value of the roughness Reynolds number parameter at which the fully turbulent flow begins to move forward of the natural transition position. It can be seen that at this Mach number, only a very small increase in $\sqrt{R_k}$ is required to move the transition position forward to within 1 inch of the roughness. At a surface Mach number of 3.67, a larger increment in $\sqrt{R_k}$ is required between the value for the first initiation of transition due to the roughness and the value for full turbulence in the vicinity of the roughness. Although almost complete forward movement in transition occurs with only a factor of two increment in $\sqrt{R_k}$ at this Mach number, the trend between the Mach number of 1.90 and 3.67 indicates that it may become increasingly more difficult to fix transition near roughness at higher Mach numbers. More research is required to clarify this possibility. At Mach numbers up to the order of 4, however, the present compilation of data can be used to estimate the maximum permissible three-dimensional roughness height that will not cause premature transition on aircraft in flight if a value of $R_{k,t}$ near the lower boundary of the data is selected. In wind-tunnel investigations with models of aircraft or aircraft components, it is sometimes desirable to locate artificially the position of transition. In this case, use of three-dimensional roughness elements selected on the basis of a value of $R_{k,t}$ near the upper boundary of the experimental data should prove adequate. Should this result in the use of particles larger than the minimum height required, careful application of a sparse distribution of particles to a narrow strip will minimize the drag contribution of the particles themselves, that is, the drag associated with the roughness elements other than the increment due to the forward movement in transition.

A further point to be made concerns the effect of laminar stability on the lateral spread of the turbulence behind a roughness particle. Inasmuch as increased stability increases the extent of laminar flow on a smooth surface, it might be expected that increased stability could decrease the rate at which turbulence behind a roughness particle propagates laterally into the laminar surroundings. Only a limited amount of information is available on this subject. Measurements were made at low speed of the lateral contamination on a large sphere behind roughness located at various positions where the location determined the degree of stability due to the favorable pressure gradient (ref. 10). Measurements were also made at a Mach number of 2 on a flat plate where the stability was increased by surface cooling (ref. 13). In neither case did an increase in laminar stability have any appreciable effect on the lateral spread of turbulence. For these experiments, however, complete laminar stability was not attained. Additional research at higher Mach numbers and greater amounts of cooling would be desirable.

A final point to be emphasized concerns the effect on transition of distributed three-dimensional roughness of various heights. For this case, it is not the root-mean-square value of the surface roughness that determines the onset of transition due to the roughness, but rather the individual projections of maximum height. These tallest particles reach the critical value of roughness Reynolds number first. Because of the lateral spread of turbulence behind the roughness, a few strategically placed particles larger than the root-mean-square roughness can cause turbulent flow over most of a surface for conditions where laminar flow might be expected if only the root-mean-square value were considered.

CONCLUDING REMARKS

The transition-triggering mechanism of three-dimensional-type surface roughness appears to be the same at supersonic and subsonic speeds. In either case, a Reynolds number based on the height of the roughness and the local flow conditions at the top of the roughness can be used to predict with reasonable accuracy the height of three-dimensional roughness required to cause transition. Neither the critical three-dimensional roughness Reynolds number nor the lateral spread of turbulence behind the roughness is changed to any important extent by increasing the laminar boundary-layer stability to theoretically small disturbances. Therefore, for a given stream Mach number and Reynolds number, surface cooling, boundary-layer suction, or a favorable pressure gradient will, in the presence of roughness, promote rather than delay transition. A favorable effect of stability on permissible two-dimensional-type disturbances, however, is possible. Further research on the value of critical roughness Reynolds number and on the interval in roughness Reynolds number between the initiation of turbulence and fully developed turbulent flow in the vicinity of the roughness would be desirable at Mach numbers greater than 4.

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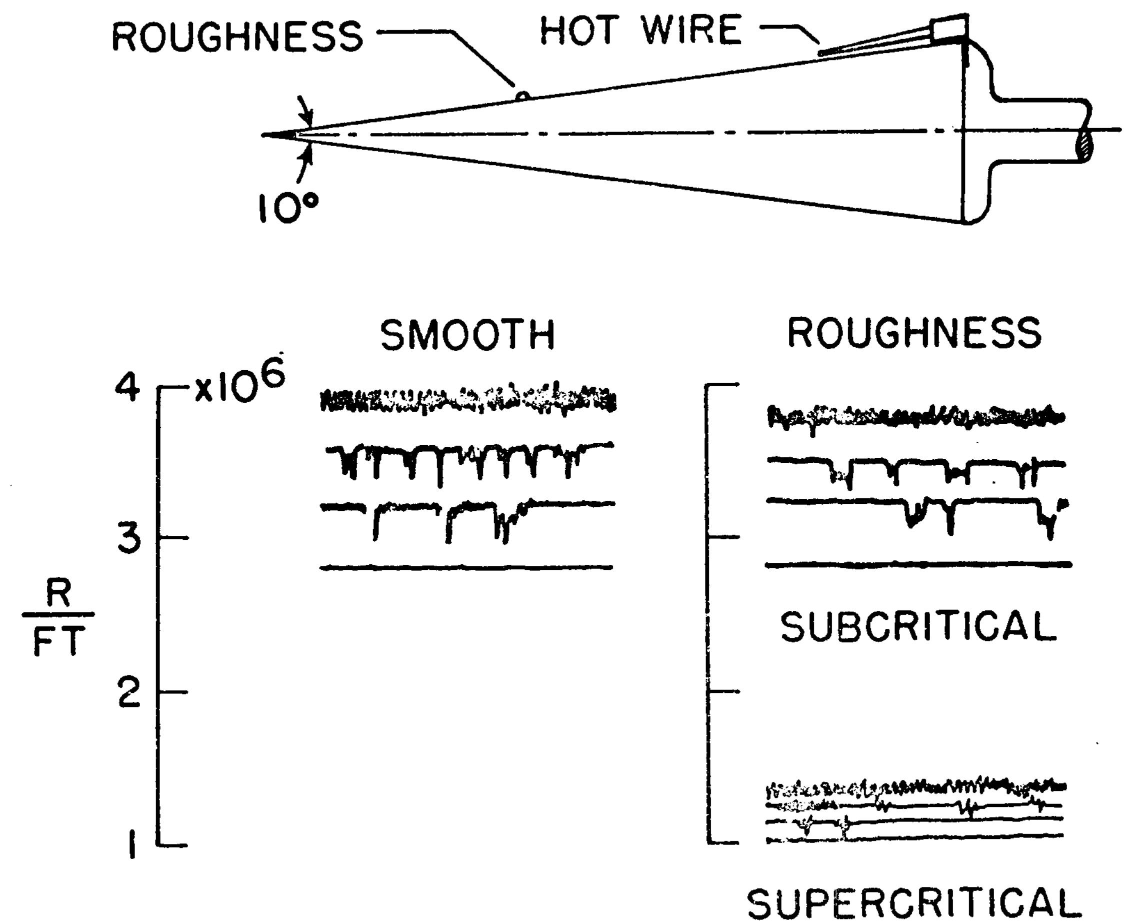


Figure 1.- Comparison of oscillograph records for a smooth 10° cone and for a cone with subcritical and supercritical roughness. $M_\infty = 2.01$.

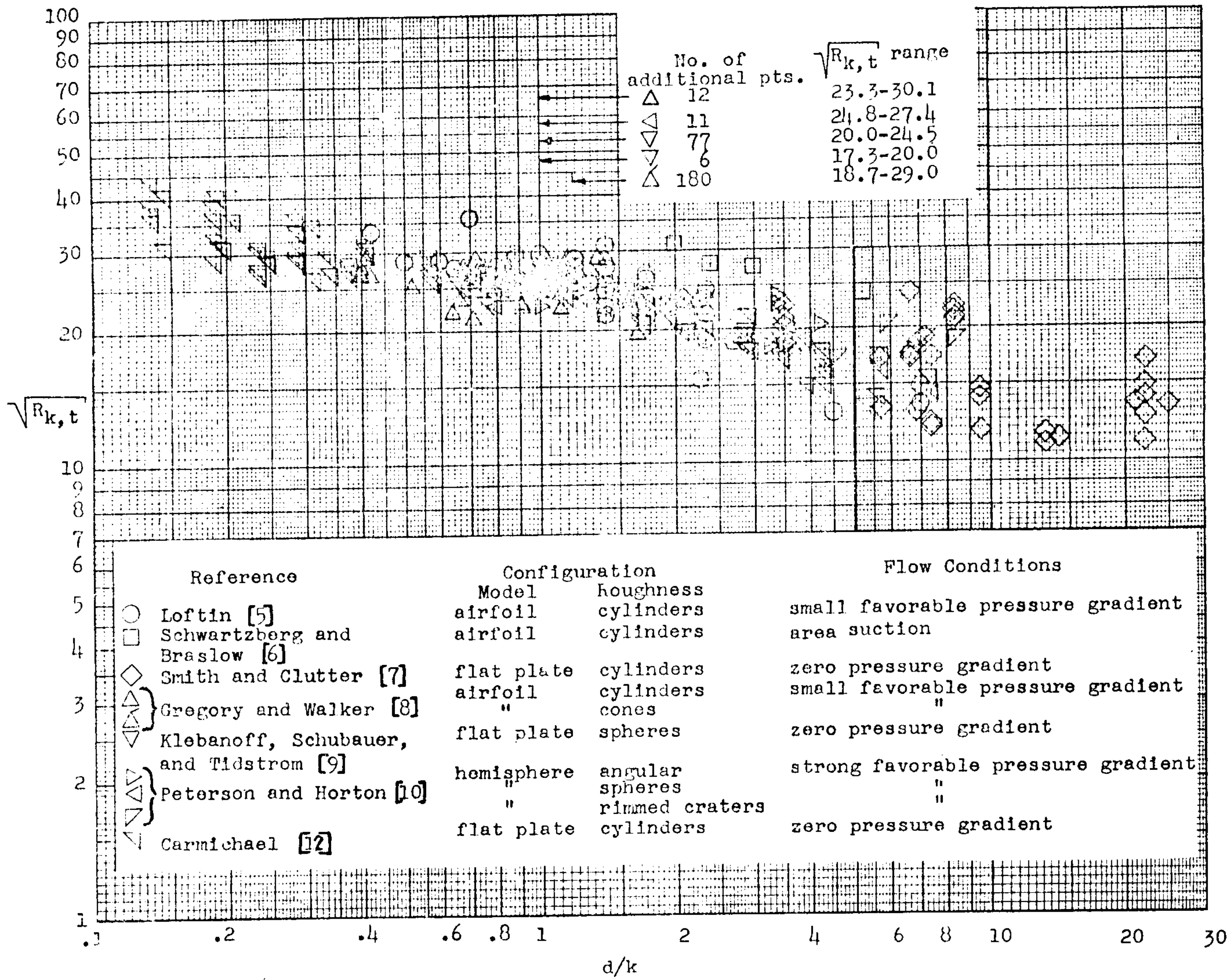


Figure 2.- Low-speed correlation of three-dimensional roughness transition data in terms of the local roughness Reynolds number and the roughness shape parameter.

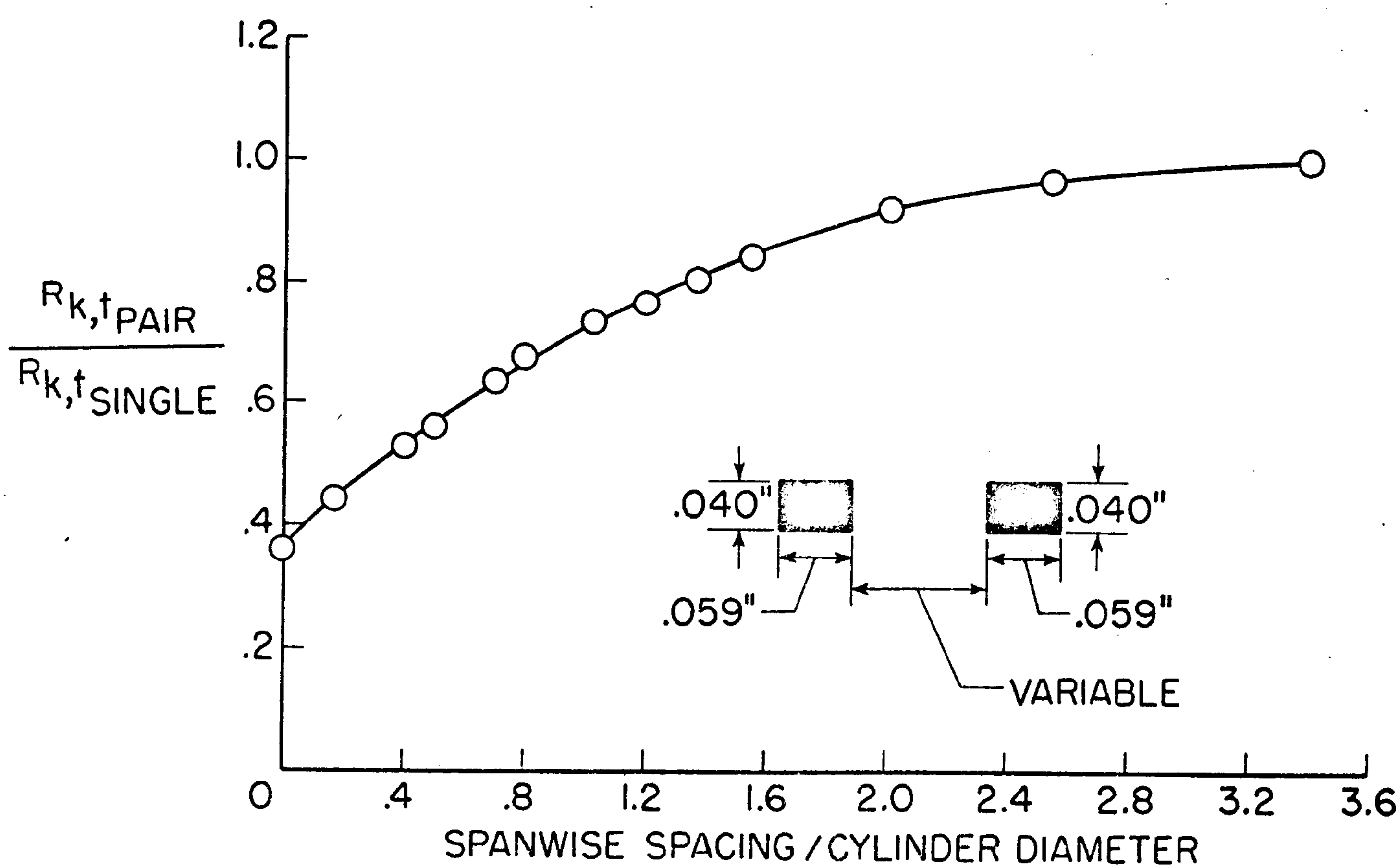


Figure 3.- Effect of spanwise spacing of pairs of cylindrical elements on the roughness Reynolds number for transition.

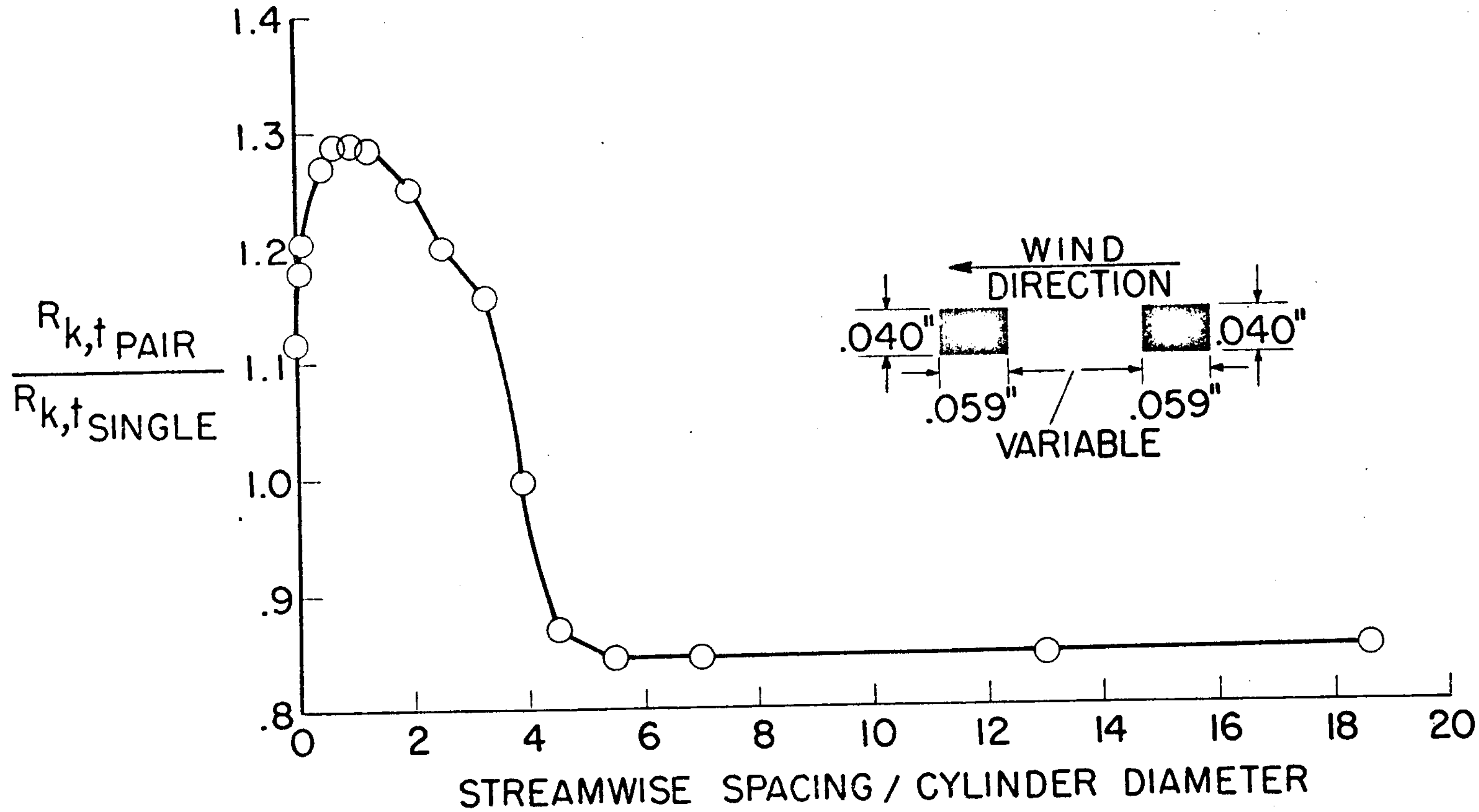
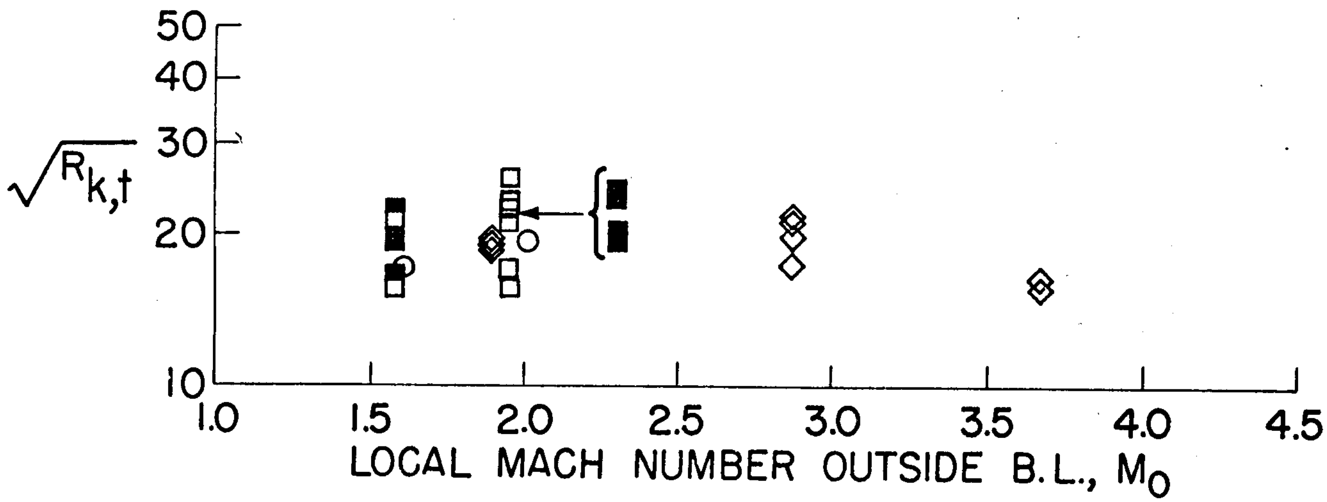


Figure 4.- Effect of streamwise spacing of pairs of cylindrical elements on the roughness Reynolds number for transition.



	REFERENCE	CONFIGURATION	ROUGH.	T_w/T_O
○ 13	BRASLOW, KNOX, & HORTON	FLAT PLATE	SPHERICAL	ADIAB.
□	"	CONE	GRANULAR	"
■	"	"	"	M_O=1.58, 1.289; M_O=1.95, 1.423
◇ 14	VAN DRIEST & MC CAULEY	"	SPHERICAL	ADIAB.

Figure 5.- Effect of supersonic Mach number on the roughness Reynolds number for transition.

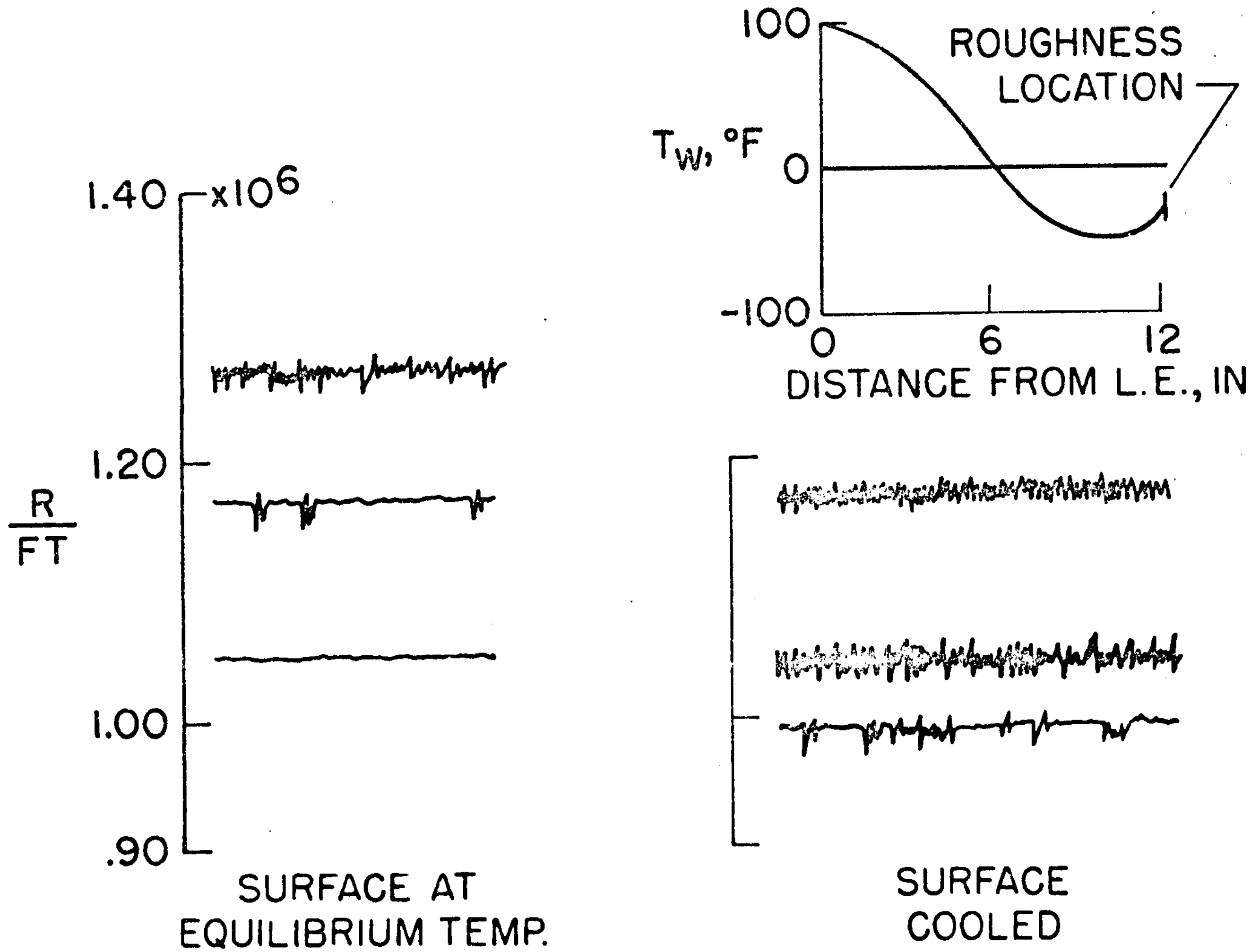


Figure 6.- Comparison of oscillograph records for 10° cone surface near adiabatic-wall temperature and cooled; 0.017-inch roughness at 12.5 inches from apex; $M_{\infty} = 2.01$.

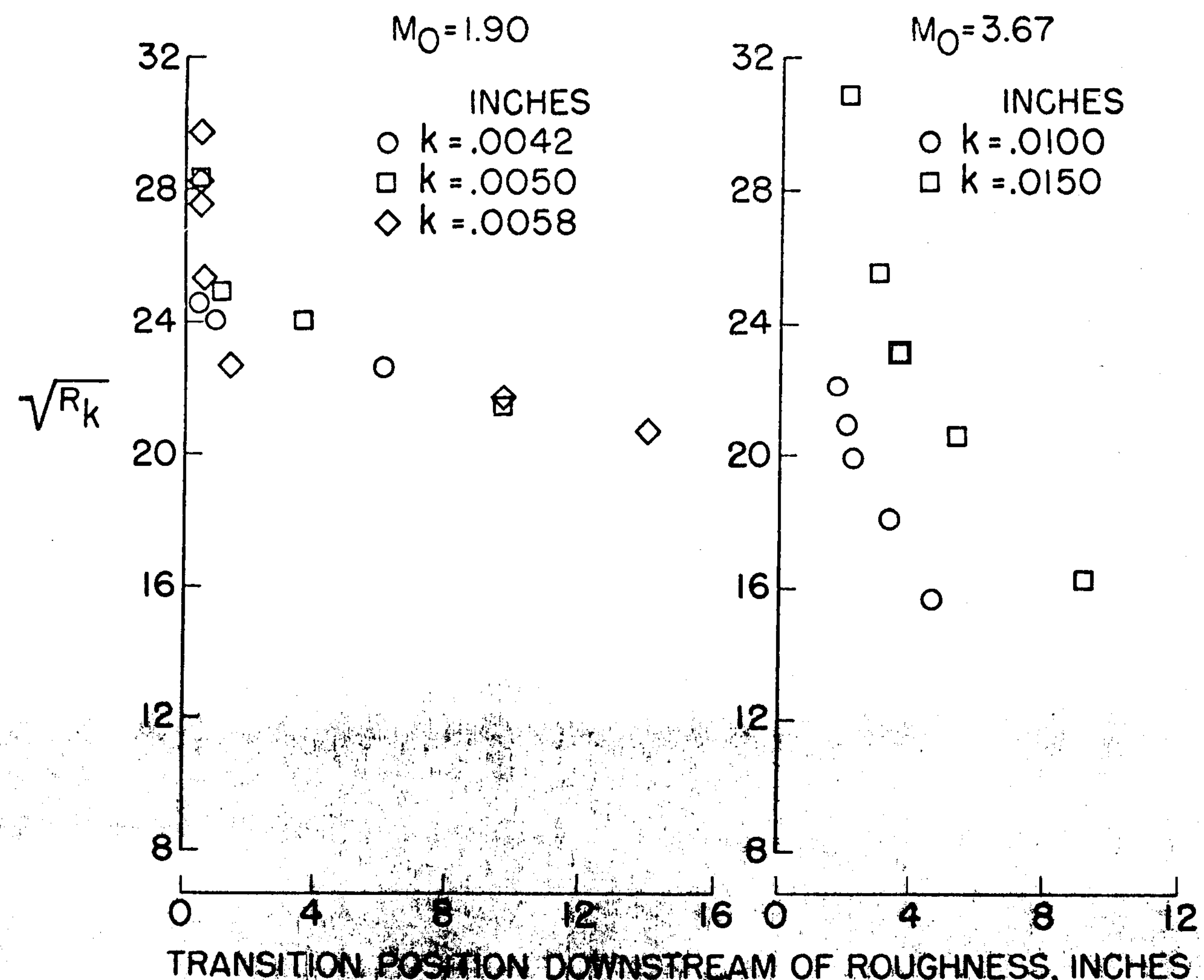


Figure 7.- Forward movement of fully developed turbulent boundary layer with incr[illegible] roughness Reynolds number.